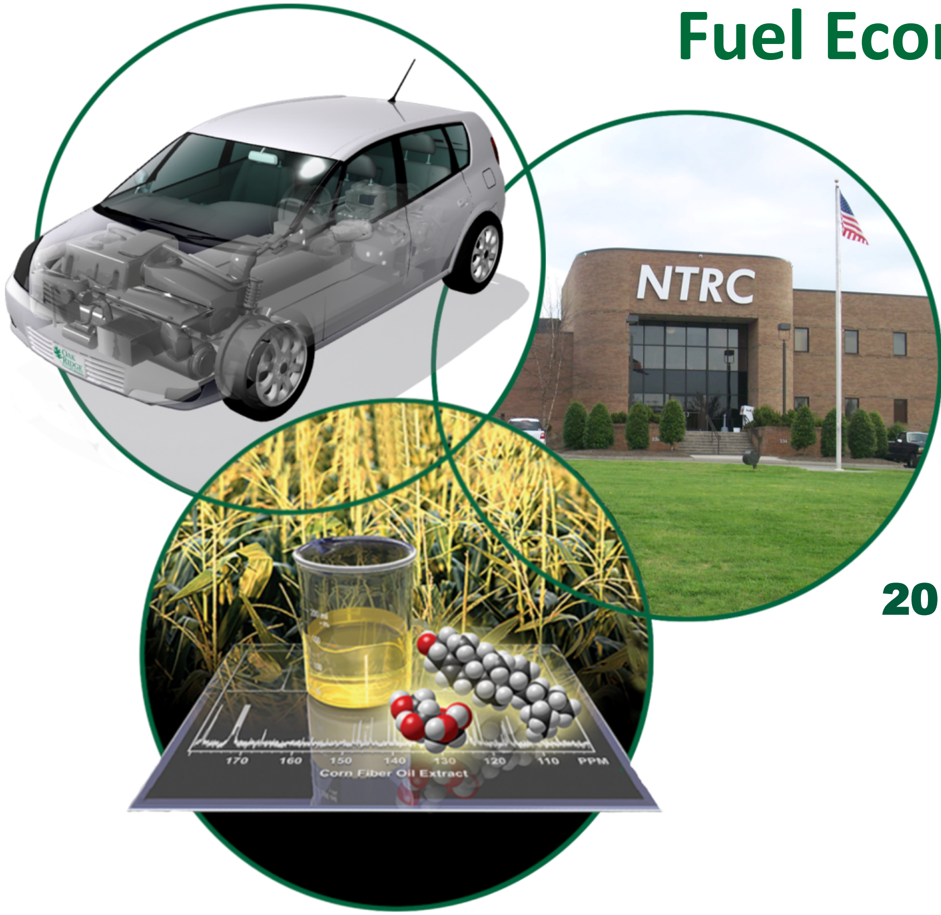
Hybridization Technology Impact on Transit Bus Fuel Economy and Emissions Control



Zhiming Gao, Tim LaClair, Stuart Daw, and, David Smith

Oak Ridge National Laboratory

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Lee Slezak and David Anderson
Vehicle and Systems Simulation and Testing (VSST)
Vehicle Technologies Office
US Department of Energy

U.S. DEPARTMENT OF ENERGY

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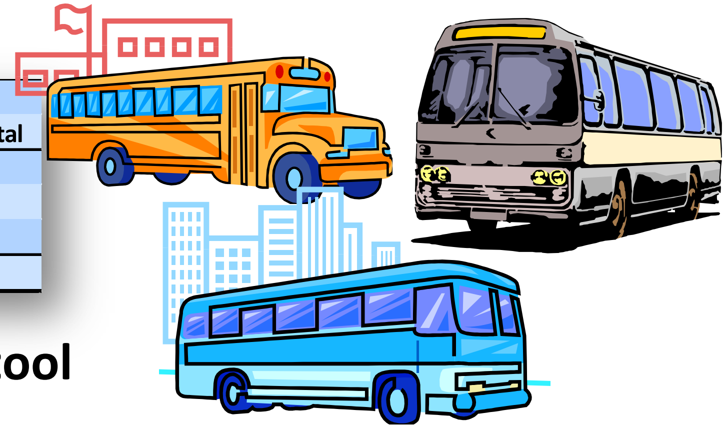
Introduction

Included among seven million medium-duty (MD) vehicle in U.S., there is a significant number of buses

- Transit bus
- Intercity bus
- School bus

Bus Transporation Energy Use in 2011		
Unit	Trillion Btu	% of HWY Total
Transit Bus	91.5	0.30%
Intercity Bus	29.8	0.10%
School Bus	73.1	0.30%
Total	190.1	0.70%



Transit bus is an important city transportation tool

- 10+ hours and 100+ miles daily
- Highly frequent stop-go routes
- Low fuel economy & significant $$$ cost

One of decent solutions is bus hybridization

$26 Billion/year subsidies for city transit buses VS. $35 Billion DOE 2013 Budget

Our Objective and Approach

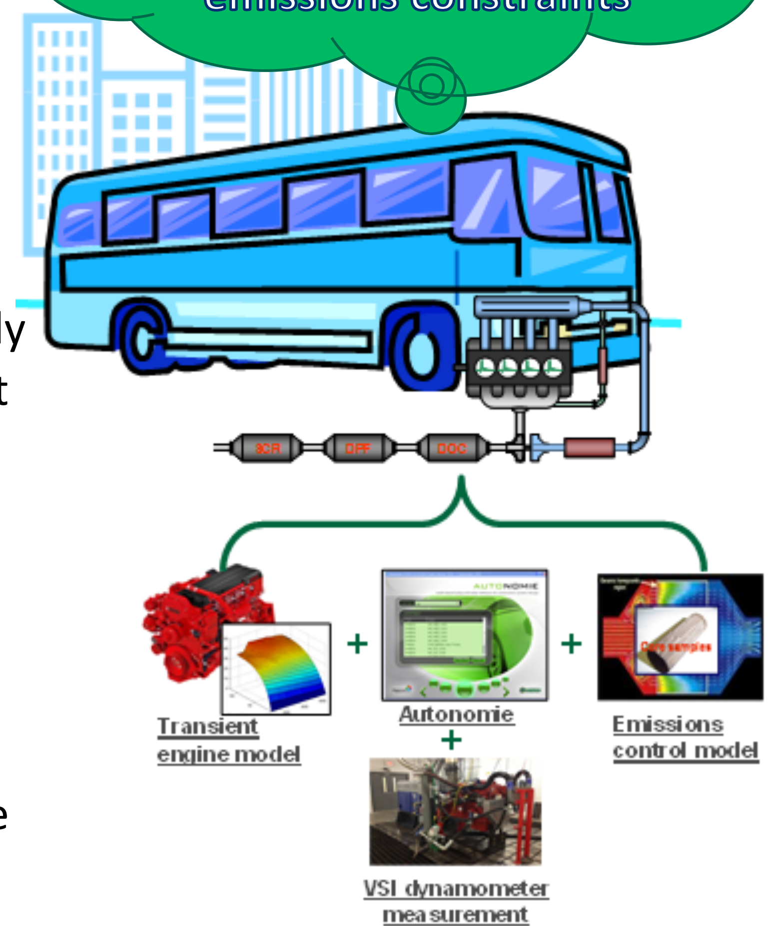
Develop the approaches for optimizing bus hybridization to lower fuel consumption within emissions constraints

R&D Objective

- Utilize simulation tool to compare the estimated fuel economy and emissions between conventional and hybrid transit buses
- Identify potential advantages and technical barriers for hybrid bus technology

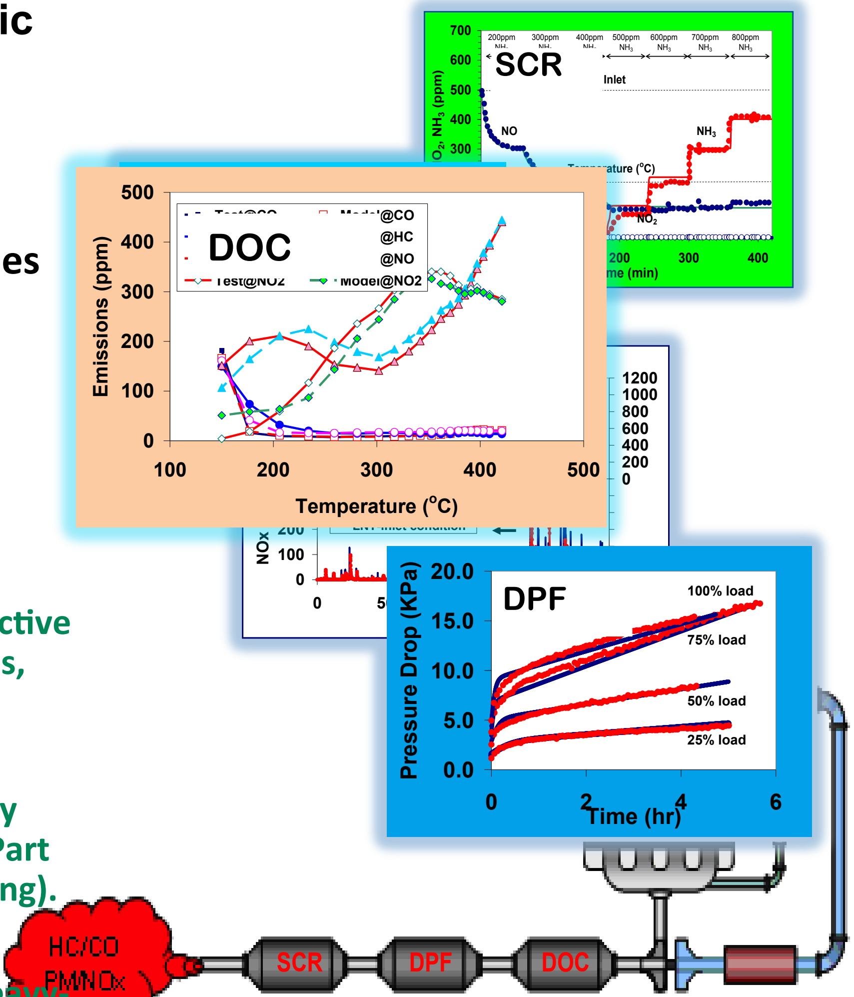
Approach

- Develop computationally efficient and physically consistent engine & aftertreatment component models
- Integrate the components in transient bus hybrid fuel economy and emission control simulations using Autonomie
- Exploit the impact of city bus powertrain configurations on fuel consumption and emissions control over representative city drive cycles



Our Engine and Aftertreatment Models

- **Low-order, physically consistent global kinetic models for diesel exhaust emission controls**
- **Low-order engine models for transient exhaust properties and fuel consumption based on corrected steady-state engine maps**
- **Vehicle system simulations over transient drive cycles in Autonomie integrated with these models**



DOC/DPF/SCR: PM/NOx/HC/CO reduction

List of References for the component models

- Z. Gao et.al., A Proposed Methodology for Estimating Transient Engine-out Temperature and Emissions from Steady-State Maps, Int. J. Engine Res., 11(2), 2010. (Transient engine modeling)
- Z. Gao et.al., Simulation of Catalytic Oxidation and Selective catalytic NOx Reduction in Lean-Exhaust Hybrid Vehicles, SAE paper 2012-01-1304 (DOC and SCR modeling).
- Z. Gao et.al., Simulating the Impact of Premixed Charge Compression Ignition on Light-Duty Diesel Fuel Economy and Emissions of Particulates and NOx, Proc. IMechE - Part D: J. Automobile Engineering, 227(1), 2013 (DPF modeling).
- C.S. Daw et.al., Simulated Fuel Economy and Emissions Performance during City and Interstate Driving For a Heavy-Duty Hybrid Truck, SAE Int. J. Commer. Veh. 6(1), 2013 (DOC/DPF/SCR and new SCR parameters).

Bus Configuration and Drive Cycle

Conventional bus

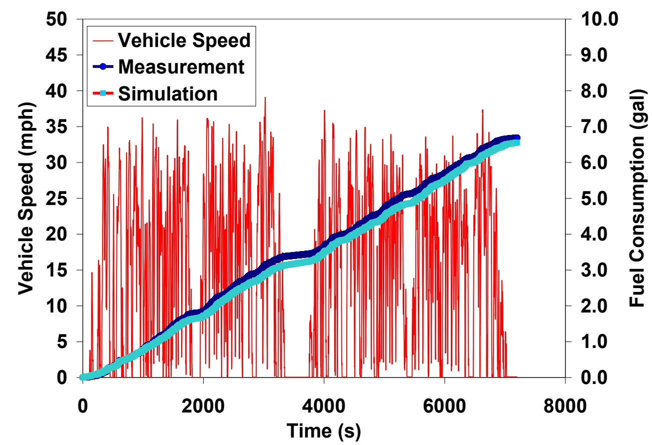
- 2005 Optima LF-34 Bus (mass:11,636kg)
- A 5.9L conventional diesel engine
- 5-speed auto transmissions
- Coefficient of drag: 0.79
- Rolling resistance: 0.0098
- Frontal area: 8.5m^2
- Accessory load: 360w EE/6790W ME
- Non-optimal Aftertreatment configuration: 2.3-L DOC/ 9.7-L DPF/7.7-L SCR

Pre-transmission parallel hybrid bus

- Motor:120kw-max/60kw-cont/920Nm-max
- Battery: 28Ah, 324V normal voltage, 140kw max-dischg, 120kw max-chg
- Accessory load: 2490w EE/1580W ME
- Hybrid mass penalty: 200kg
- Sustainable battery charge control strategy

City bus drive cycle

- Central Business District (CBD) cycle
- Orange County Transient Authority (OCTA) cycle
- Manhattan Bus Cycle (Manhattan)
- Washington Metropolitan Area Transit Authority (WMATA) cycle
- New York Bus Cycle (NYBC)
- KAT cycle with real-road grade



Conventional bus validation: simulated 6.68gal vs. tested 6.56gal over a 28.6 mile real-road drive cycle

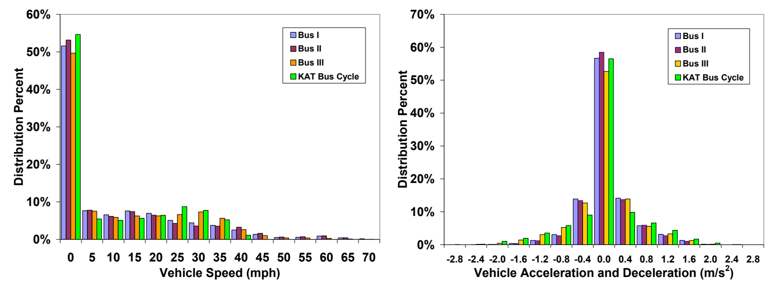
- The measured bus powered by a 5.9L Cummins ISB-02 engine
- The simulated bus powered by a downsized 5.9L engine from a 7.2L Caterpillar engine

Cycle	CBD	OCTA	Manhattan	WMATA	NYBC	KAT*
Duration (s)	567	1909	2178	1839	620	7200
Distance (mile)	2.01	6.54	4.13	4.26	0.61	17.15
Avg. Speed (mph)	12.73	12.33	6.83	8.34	3.57	8.57
Max Speed (mph)	20.00	40.63	25.30	47.50	30.70	39.06
% Idle Time	20.6%	26.9%	39.2%	43.8%	68.9%	54.5%
Max Accel (m/s^2)	2.30	4.06	4.60	3.00	6.10	2.12
Max Decel (m/s^2)	-4.70	-5.13	-5.60	-4.50	-4.30	-2.28

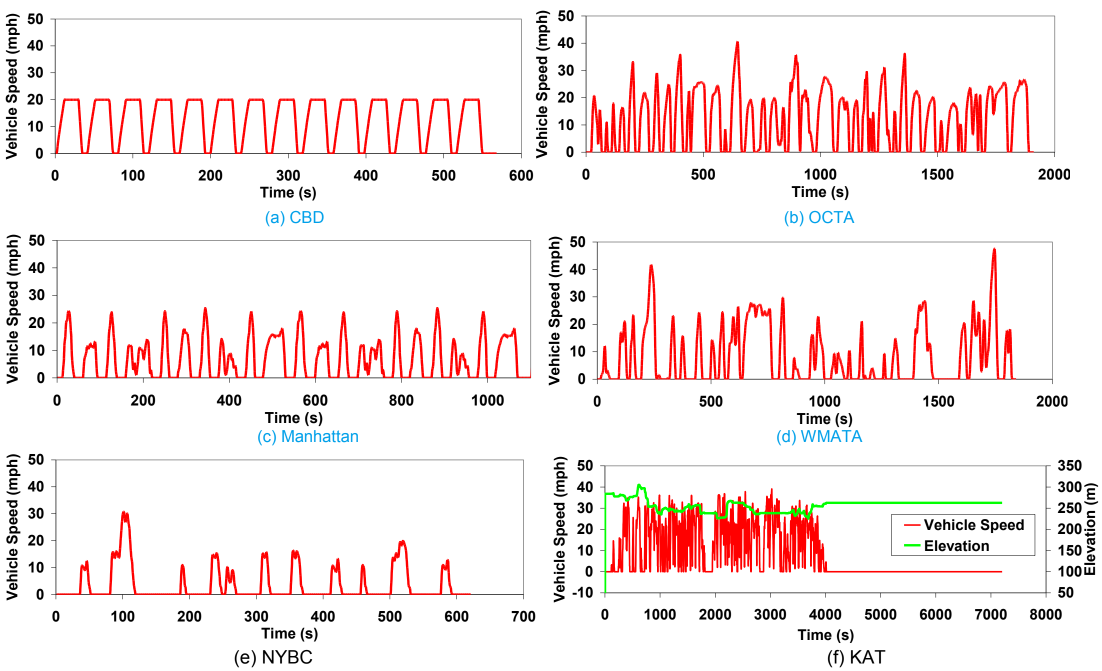
*KAT cycle constructed using 1 year of measurements from three buses operated by KAT in Knoxville, TN

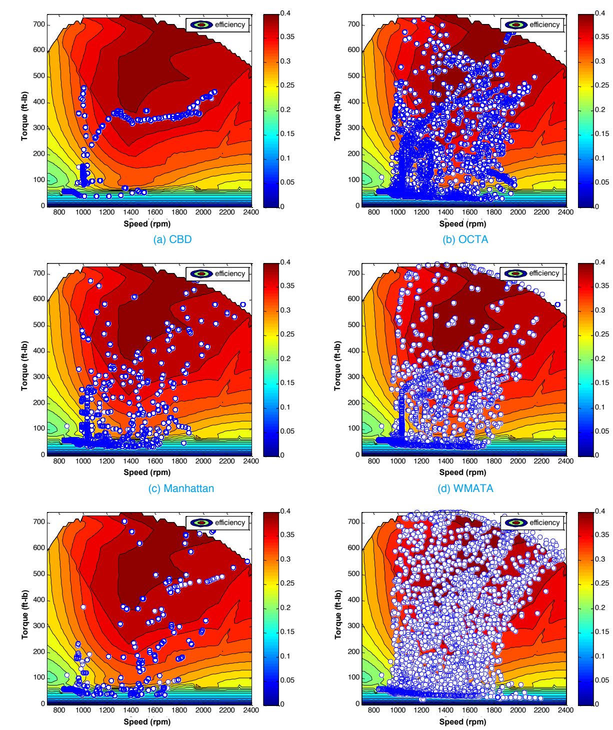
City Drive Cycles

- The CBD cycle is a "sawtooth" driving pattern with multiple repetitions of an idle, acceleration, cruise, and deceleration sequence
- The OCTA cycle reflects urban transit buses' driving patterns in Los Angeles
- The Manhattan bus cycle reflects transient bus driving patterns in Manhattan
- WMATA cycle represents transit bus driving patterns in Washington, D.C.
- The NYBC cycle reflects transit bus driving patterns in New York City.
- The KAT cycle was constructed by using the ORNL MD conventional bus database, measured data for three buses operated by KAT in Knoxville, TN
  - Two distinct types of operating conditions: frequent stop-and-go during the first 4000s, and a long idling period for the remainder of the drive cycle.



Measured speed and acceleration distributions of the Knoxville city buses compared to the constructed KAT drive cycle

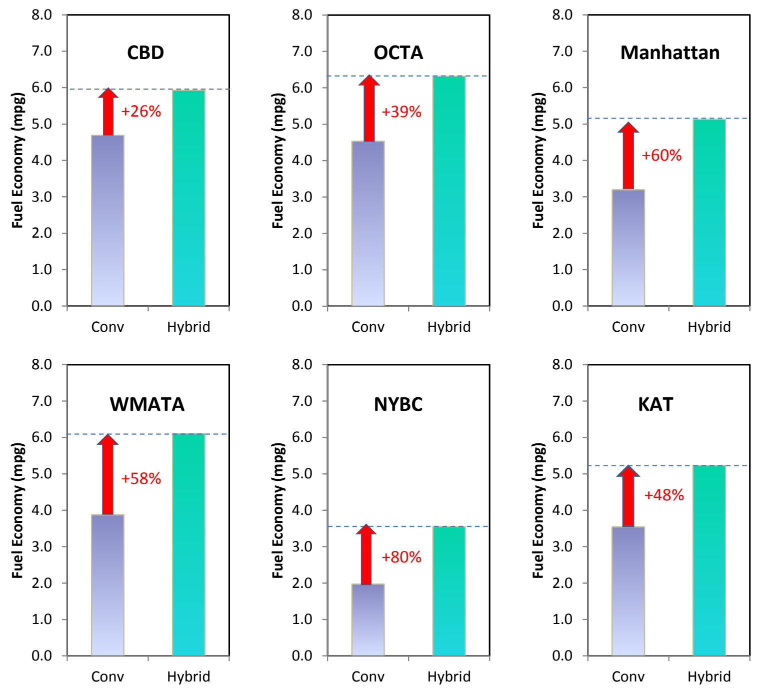


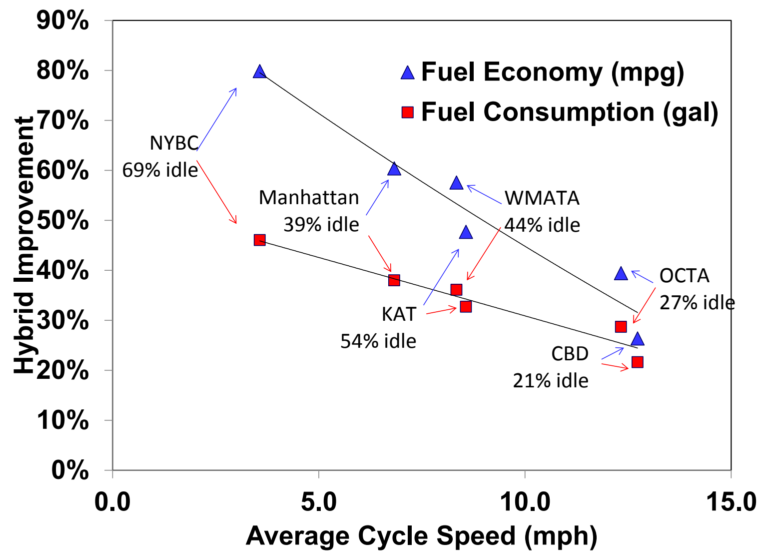


Fuel Economy of Bus Hybrid

Simulation conditions:

- Bus powertrain architecture: conventional and parallel hybrid buses powered by a conventional diesel engine
- Six city drive cycles beginning with an initial cold start from 20°C
- All bus simulations run for a period of 7200s by repeating each drive cycle





Bus hybridization saves fuel energy

- 26% - 80% in fuel economy Improvement.
- More significant fuel savings in the cycles with lower average speeds

A cycle with lower average speed usually reflects longer idle times and more braking.

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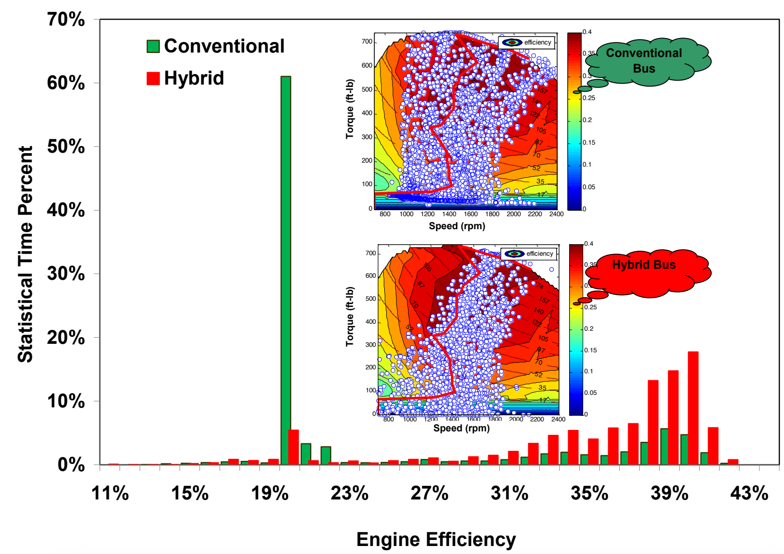
Example of Critical Factors behind Fuel Energy Savings Relevant to Hybridization

- The simulated case: KAT drive cycle beginning with a cold-start
- The main factors impacting fuel energy savings
  - A boost in the engine efficiency by operating at more favorable speeds and loads
  - Reduction of idle and accessory loads as a result of engine shutdown during stops
  - Significant brake energy recovery



<u>**Comparison of energy losses for conventional versus hybrid buses operating over the KAT drive cycle beginning with a cold-start.**</u> (Note: the total fuel energy for the conventional bus is used as a reference in both cases)

Auxiliary loads: 7.9%@conv vs. 3.6%@ hybrid

Motor loss: 0%@conv vs. 2.0%@hybrid

Battery loss: ~0%@conv vs. 0.9%@hybrid

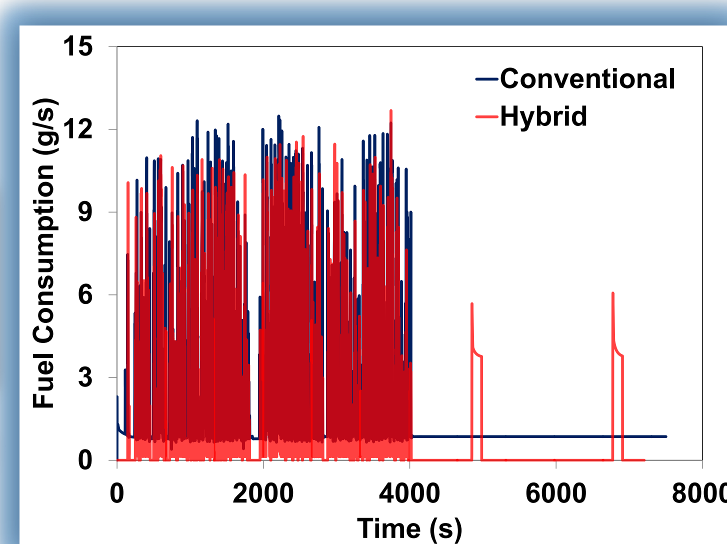
Engine loss: 67.5%@conv vs. 42.7%@hybrid

Drivetrain loss: 5.7%@conv vs. 7.8%@hybrid

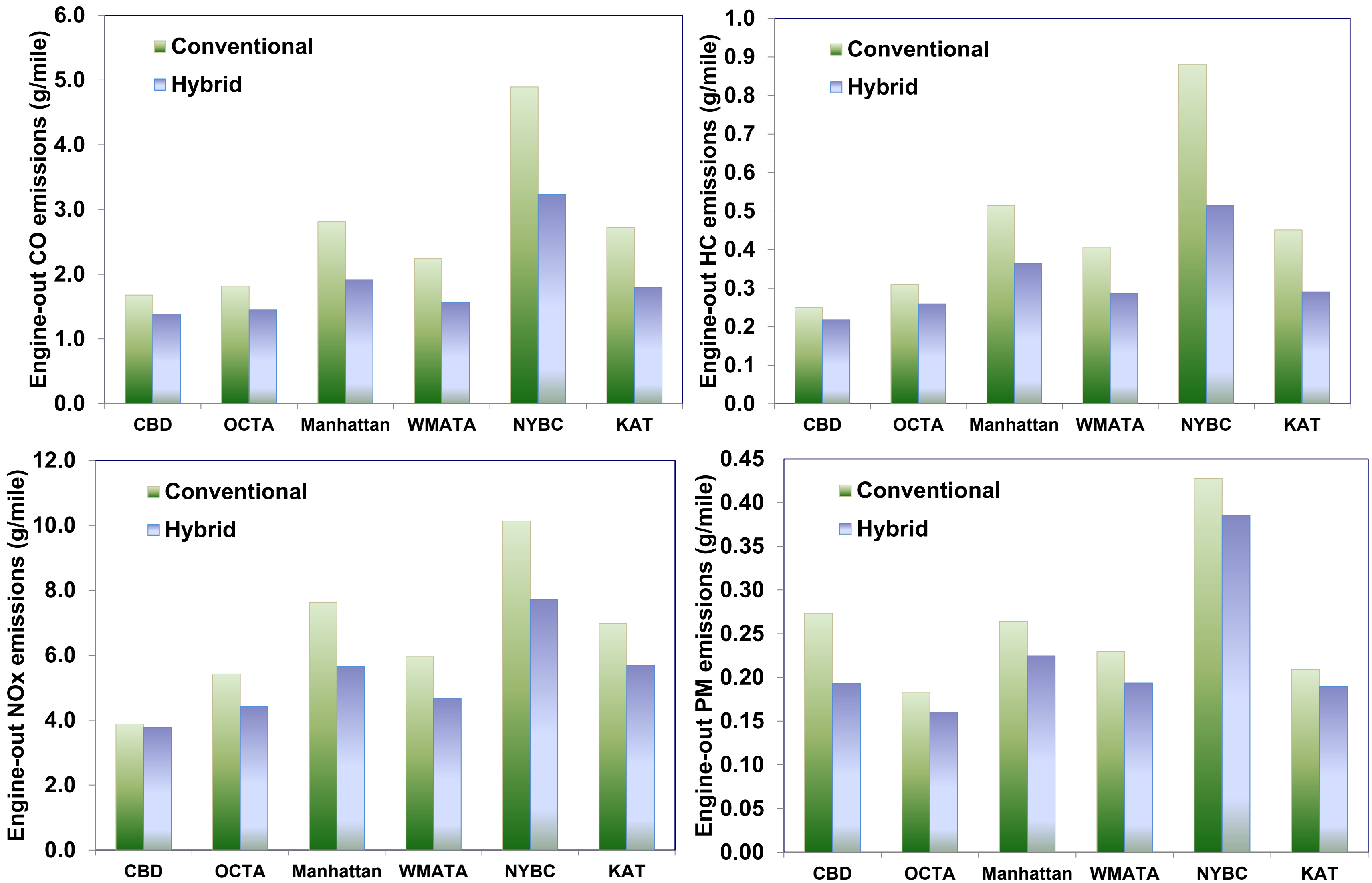
Power to wheel: 18.6%@conv vs. 9.8%@hybrid

Braking loss 12.9%@conv vs. 4.7%@hybrid

<u>**Hybridization saves 33.2% of fuel energy over the KAT cycle**</u>



Substantial Reduction of Engine-out CO, HC, NOx and PM in the Simulated Hybrid Bus



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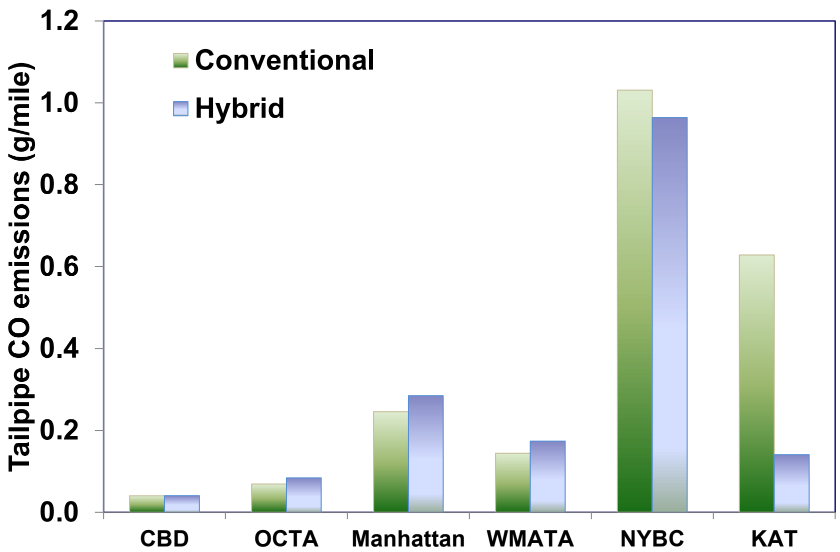
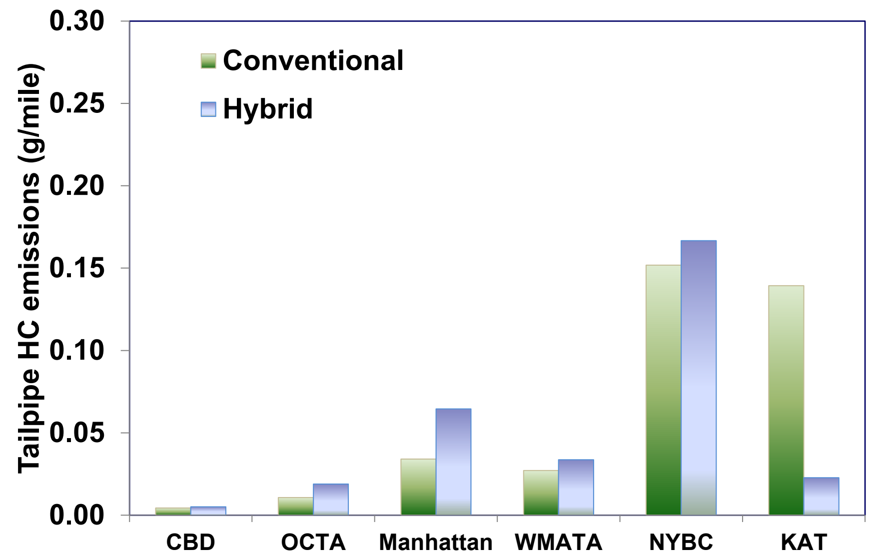
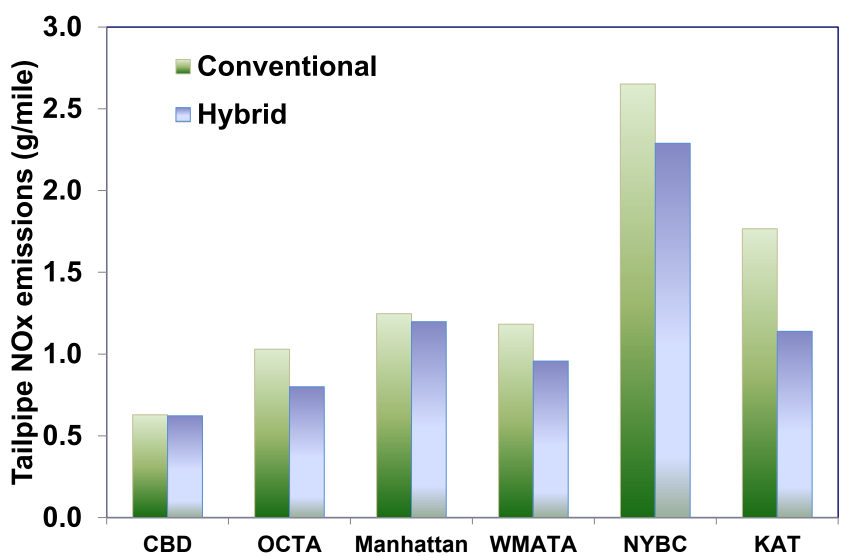
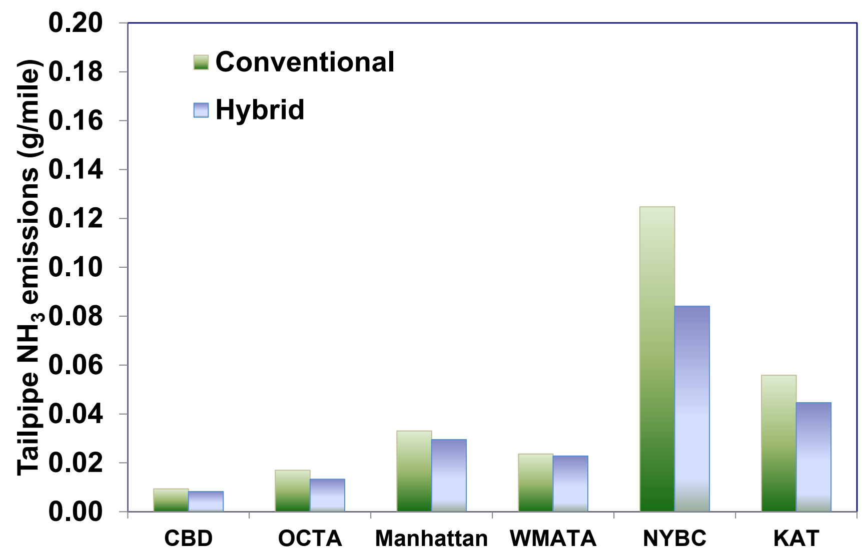
Complex Trends in Tailpipe Emissions



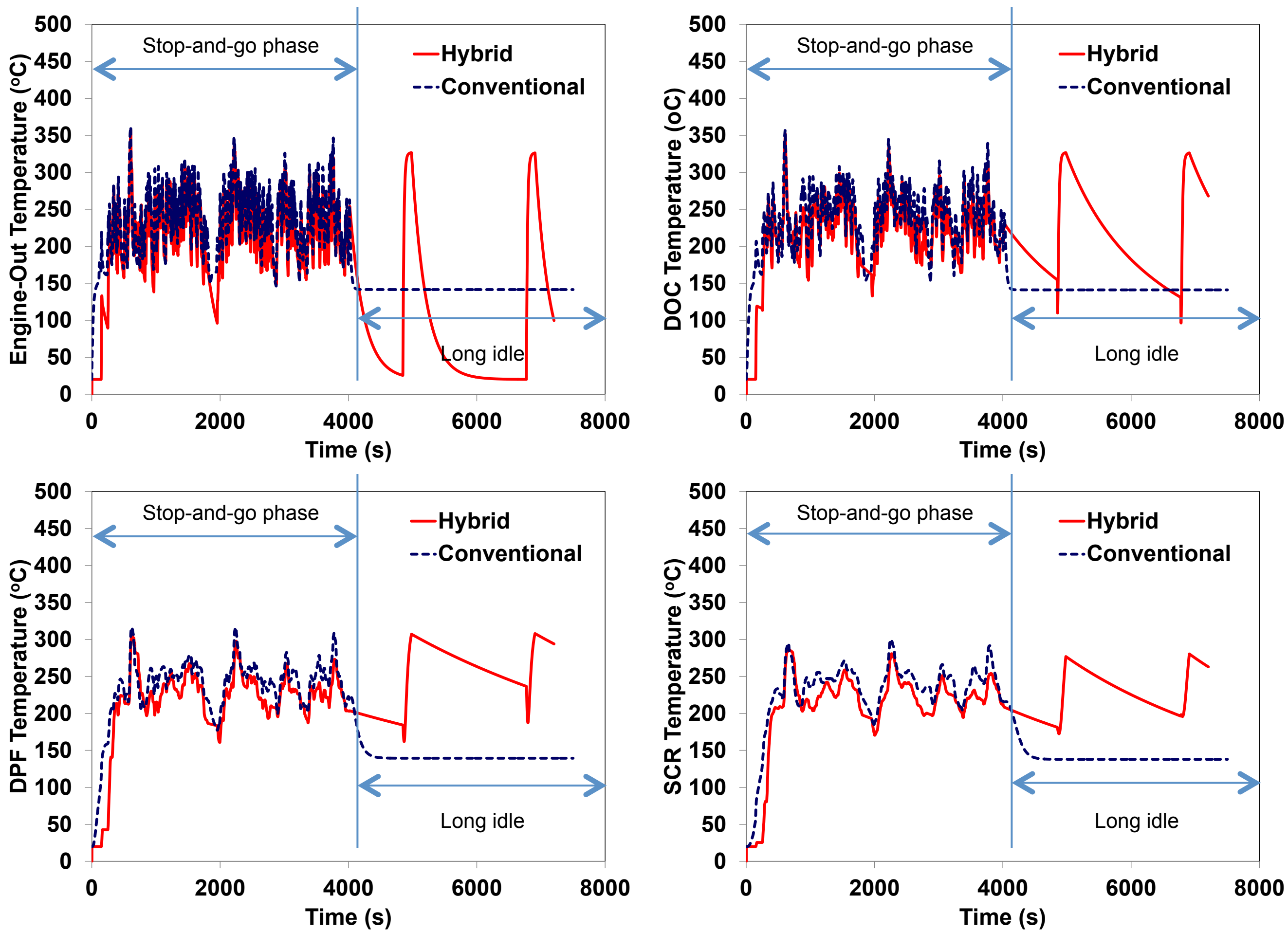






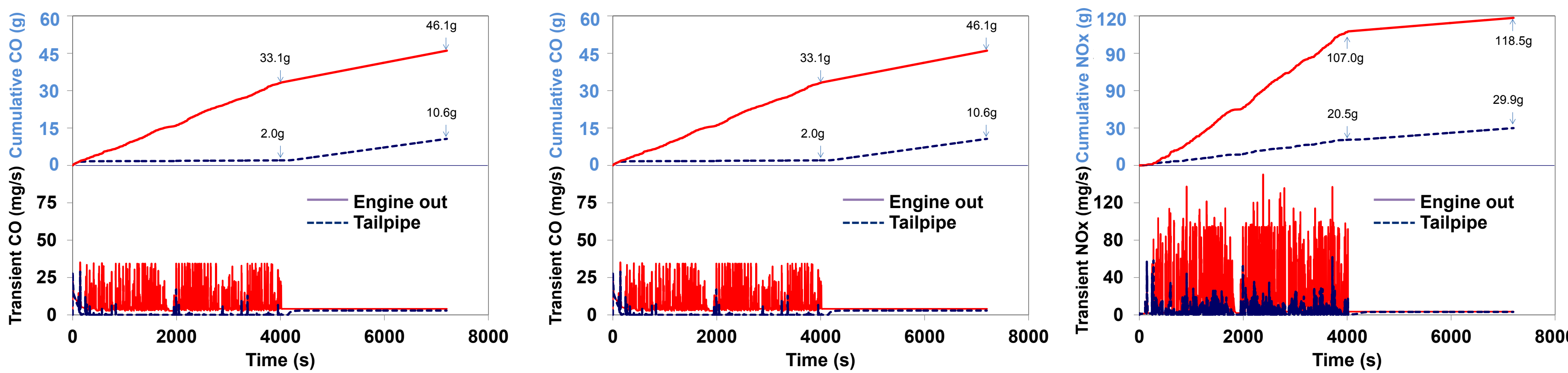
Example: Effect of Bus Hybridization on Catalytic Temperature over the 20°C Cold-Start KAT Cycle

- **Hybrid technology lowers bus catalyst temperature during the frequent stop-and-go period**
- **Periodic engine restarts boost catalyst temperature above the "light-off" during periods of long idling**

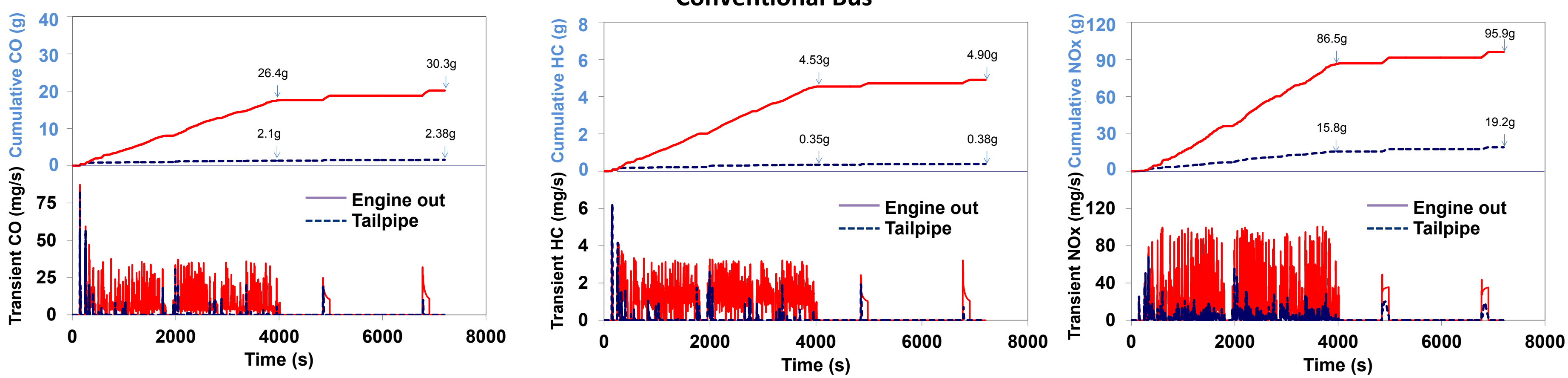


Example: Comparison of CO/HC/NOx between the Conventional and Hybrid Buses over the 20°C Cold-Start KAT Cycle

- **The hybrid bus cold start produces higher CO and HC tailpipe emissions**
- **The extended-period idle leads to significant CO and HC tailpipe emissions from the simulated conventional bus**



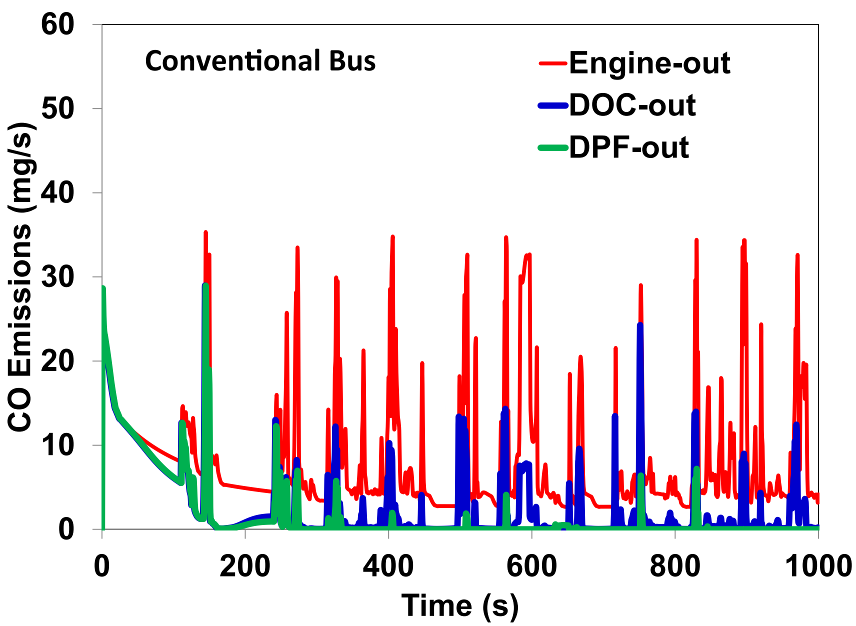
Conventional Bus

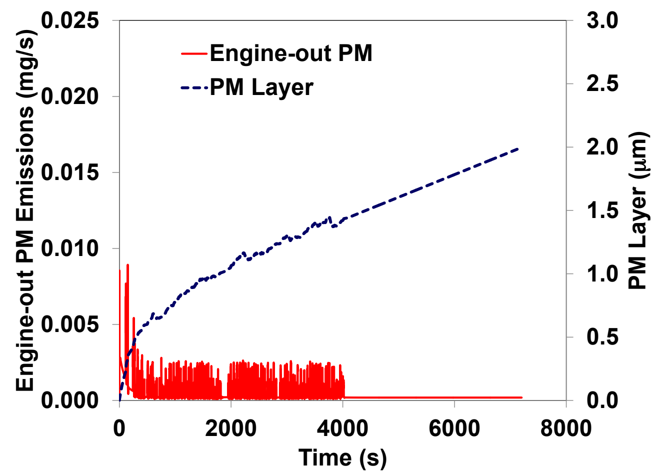


Parallel Hybrid Bus

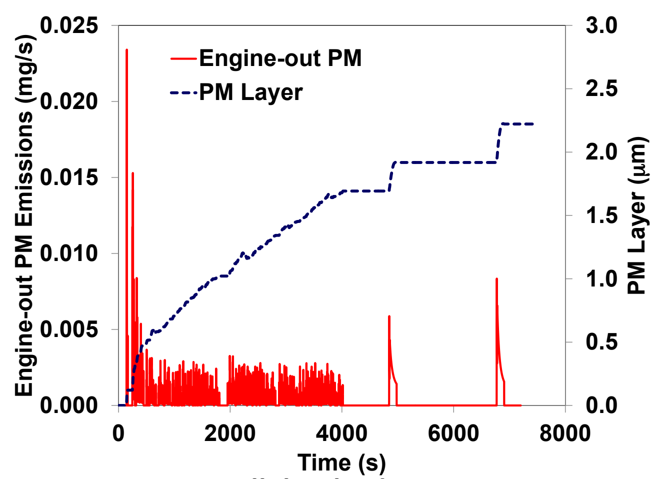
Example: Comparison of Catalytic DPF Performance in the Conventional and Hybrid Buses over the 20°C Cold-Start KAT Cycle

- **Monotonically increasing PM layer occurred in both the conventional and hybrid buses**
  - More PM accumulation for the hybrid
  - Less passive PM oxidation for the hybrid
- **0.36%-0.52% of fuel penalty caused by increasing back pressure due to PM accumulation**
- **Significant CO/HC oxidation occurred in the catalytic DPF**
  - Identical to ORNL bench-reactor testing





Conventional Bus



Parallel Hybrid Bus

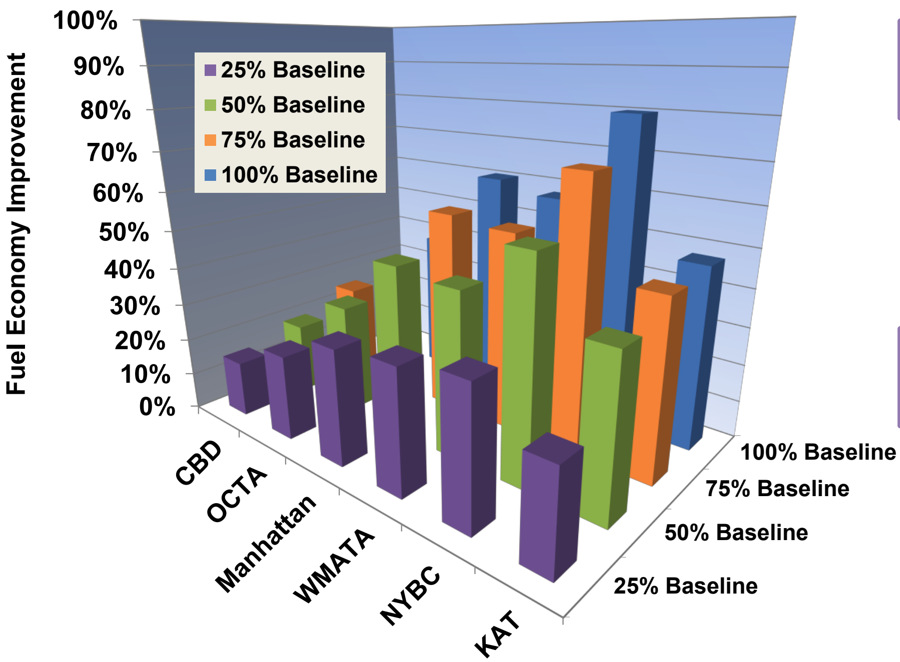
Effect of Motor and Battery Size on Fuel Economy and Component Energy Loss

Case Study

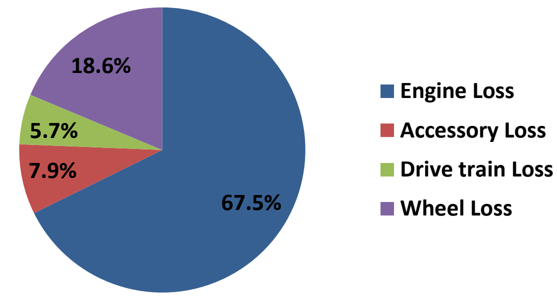
- **Bus hybridization with 100%, 75%, 50%, and 25% of baseline motor and battery sizes**

Observations for smaller motor/battery sizes

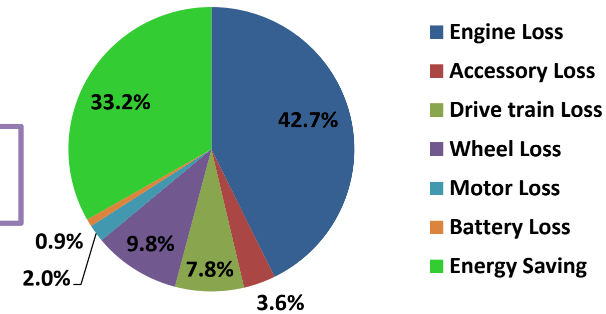
- **A lower fuel economy benefit**
- **Less opportunities for regenerative braking**
- **Still positive for reduction of idle and accessory loads**



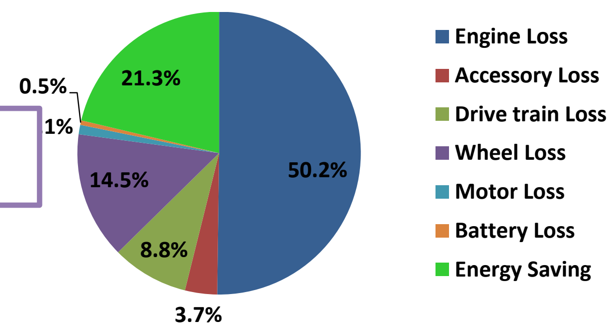
Conventional Bus



Hybrid bus with 100% baseline



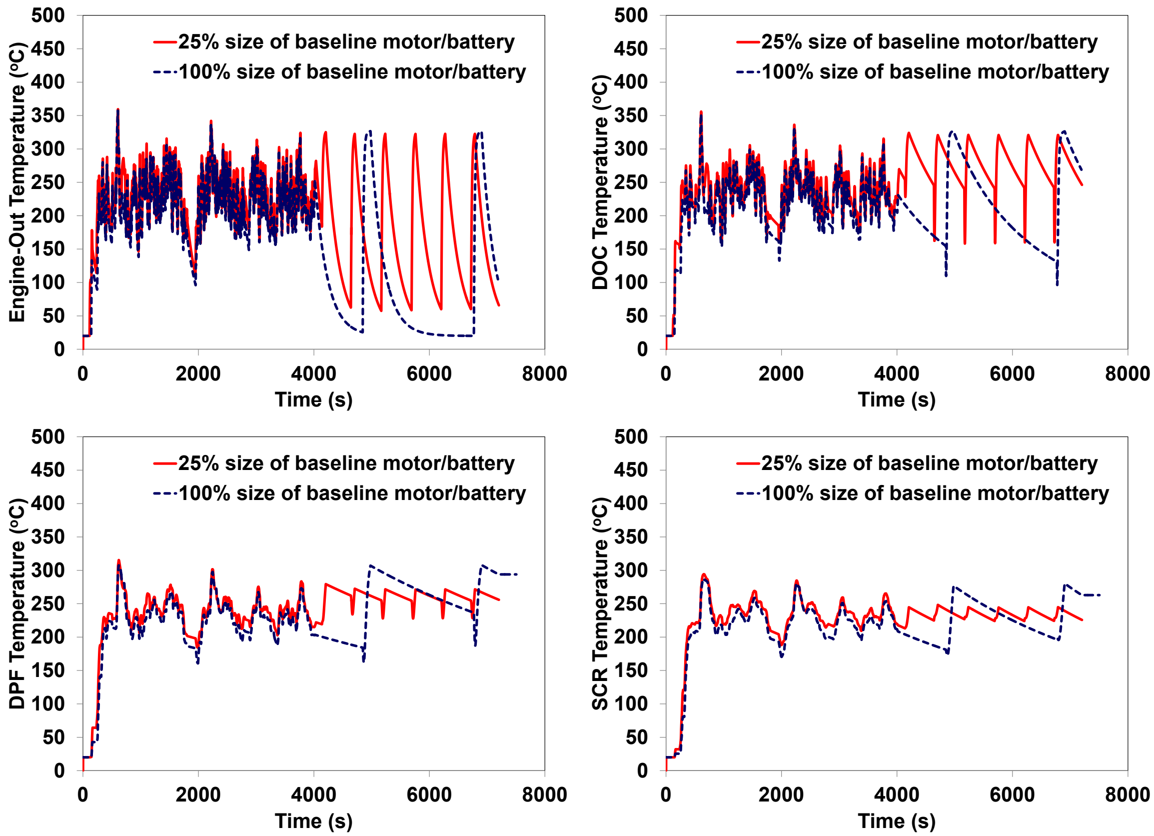
Hybrid bus with 25% baseline



Effect of Motor and Battery Size on Catalytic Temperature in the Hybrid Buses over the 20°C Cold-Start KAT Cycle

<u>The engine in the smaller hybrid turns on more frequently</u>

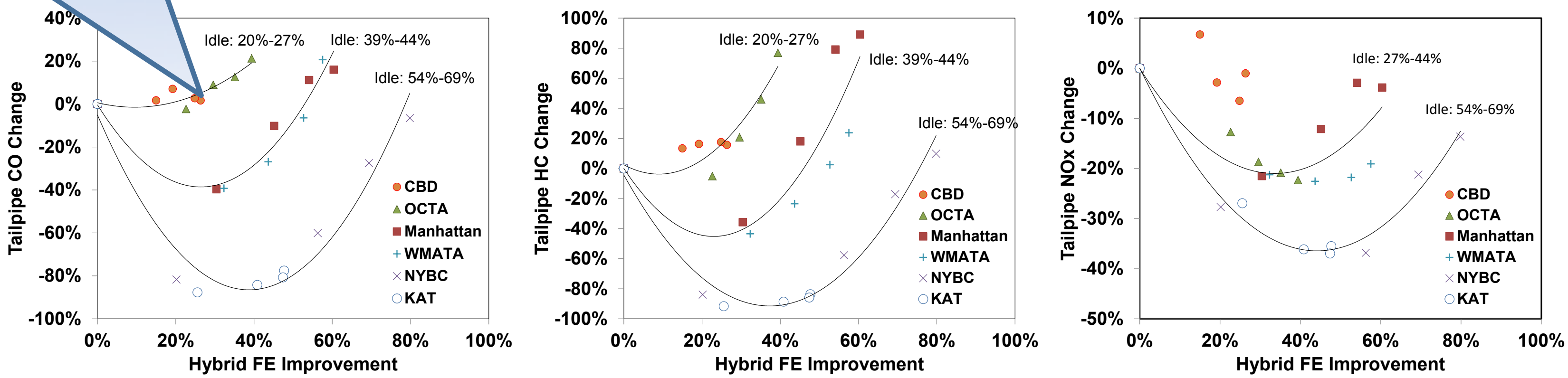
- **Increases exhaust temperature somewhat**
- **Lower engine efficiency**



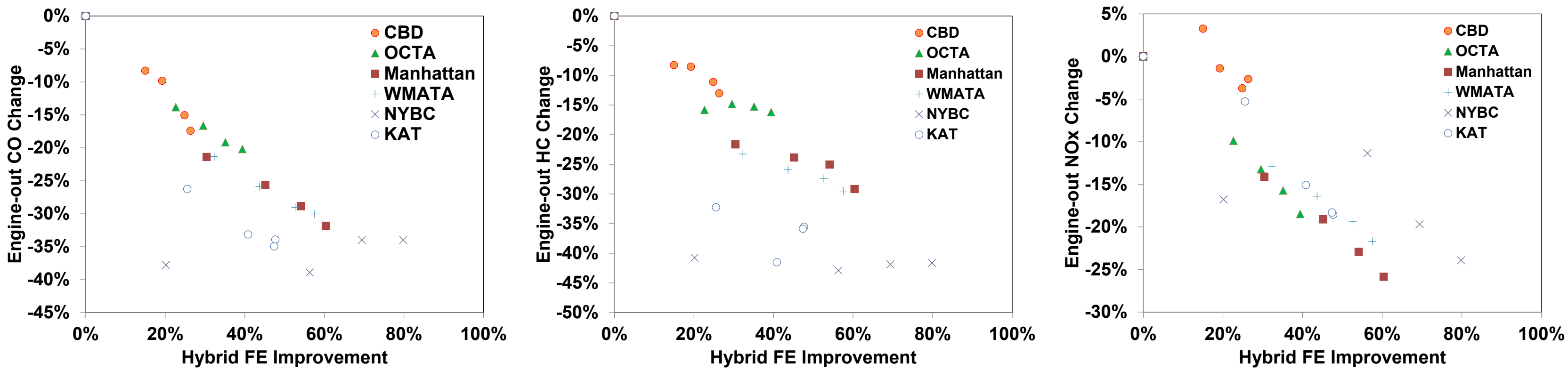
Effect of Motor and Battery Size on Emissions Control

Different drive cycles naturally cluster into various groups

- The smaller motor/battery leads to higher engine-out emissions and reduced fuel economy
- Tailpipe emissions exhibit minimums at an intermediate level of hybridization and fuel economy



(a) Tailpipe emissions



(b) Engine-out emissions

Summary

On fuel economy:

- The simulated hybrid bus exhibited significantly enhanced fuel economy, resulting from improved engine efficiency, reduced engine idling and accessory loads, and brake energy recovery
- Smaller motor/battery size combinations employed in the hybrid bus decrease the fuel economy benefit, primarily due to more frequent low-efficiency engine operation and less brake energy recovery
- The energy-saving benefits of hybridization became more significant for drive cycles with lower average cycle speeds

On emissions control

- With increased levels of hybridization, engine-out emissions tended to decrease monotonically, but tailpipe emissions demonstrated a complex behavior as a result of the sensitivity of aftertreatment catalysts to temperature.
- Tailpipe emissions appeared to reach a minimum at intermediate levels of hybridization for all drive cycles due to higher exhaust temperatures.
- Detailed tailpipe emissions trend as a function of the level of hybridization and appeared to cluster in three distinct drive cycle groups related to overall idling time.